

# Use of LCA as a development tool within early research: challenges and issues across different sectors

Alexandra C. Hetherington · Aiduan Li Borrión ·  
Owen Glyn Griffiths · Marcelle C. McManus

Received: 24 August 2012 / Accepted: 9 July 2013 / Published online: 1 August 2013  
© Springer-Verlag Berlin Heidelberg 2013

## Abstract

**Purpose** The aim of this paper is to highlight the challenges that face the use of life cycle assessment (LCA) for the development of emerging technologies. LCA has great potential for driving the development of products and processes with improved environmental credentials when used at the early research stage, not only to compare novel processing with existing commercial alternatives but to help identify environmental hotspots. Its use in this way does however provide methodological and practical difficulties, often exacerbated by the speed of analysis required to enable development decisions to be made. Awareness and understanding of the difficulties in such cases is vital for all involved with the development cycle.

**Methods** This paper employs three case studies across the diverse sectors of nanotechnology, lignocellulosic ethanol (biofuel), and novel food processes demonstrating both the synergy of issues across different sectors and highlighting the challenges when applying LCA for early research. Whilst several researchers have previously highlighted some of the issues with use of LCA techniques at an early stage, most have focused on a specific product, process development, or sector. The use of the three case studies here is specifically designed to highlight conclusively that such issues are prevalent to use of LCA in early research irrespective of the technology being assessed.

**Results and discussion** The four focus areas for the paper are system boundaries, scaling issues, data availability, and

uncertainty. Whilst some of the issues identified will be familiar to all LCA practitioners as problems shared with standard LCAs, their importance and difficulty is compounded by factors distinct to novel processes as emerging technology is often associated with unknown future applications, unknown industrial scales, and wider data gaps that contribute to the level of LCA uncertainty. These issues, in addition with others that are distinct to novel applications, such as the challenges of comparing laboratory scale data with well-established commercial processing, are exacerbated by the requirement for rapid analysis to enable development decisions to be made. **Conclusions** Based on the challenges and issues highlighted via illustration through the three case studies, it is clear that whilst transparency of information is paramount for standard LCAs, the sensitivities, complexities, and uncertainties surrounding LCAs for early research are critical. Full reporting and understanding of these must be established prior to utilising such data as part of the development cycle.

**Keywords** Biofuel · Emerging technologies · Food processing · Life cycle assessment · Nanotechnology · Novel · Scale-up

## 1 Introduction

As a tool designed to quantify the full range of environmental impacts within a system, life cycle assessment (LCA) has traditionally been undertaken retrospectively, using data from existing large scale processes. However, great potential for environmental improvement exists using LCA within the design stage of any product or process where it is estimated that about 80 % of all environmental effects associated with a product are determined in the design phase of development (Tischner et al. 2000). Indeed, determining where improvements can be made whilst a process is still at the laboratory stage can be key to unlocking the environmental improvement

---

Responsible editor: Stig Irving Olsen

A. C. Hetherington (✉) · A. L. Borrión · O. G. Griffiths ·  
M. C. McManus

Sustainable Energy Research Team, Department of Mechanical  
Engineering, University of Bath, Bath BA2 7AY, UK  
e-mail: sert@lists.bath.ac.uk

A. C. Hetherington  
e-mail: a.hetherington@bath.ac.uk

potential, forming the basis of ecodesign. Its use through the more generic life cycle thinking is also encouraged through numerous policies and legislation, such as those based on producer responsibility (e.g., EU Directives such as the WEEE Directive (EC 2006), End of Life Vehicle Directive (EC 2003), and those that promote the use of aspects of LCA such as the Renewable Energy Directive (EC 2009).

Whilst a myriad of methodological challenges are debated within the LCA community (Ekvall and Weidema 2004; Roy et al. 2009), there is a general consensus on LCA's suitability as an effective tool for determining environmental performance (Finnveden et al. 2009) and it is used widely as a decision-making tool in process selection, design, and optimization (Del Borghi et al. 2007). Koller et al. (2000) and Tufvesson et al. (2013) note that full-scale LCA is often thought of as too difficult or time consuming to pursue at the research or development stage of a new product or process. There are certainly a number of methodological and practical difficulties that arise from using LCA at this stage and Kunnari et al. (2009) discuss options for methodological changes, based on the work of Nielsen and Wenzel (2002) who advocate the use of a stepwise LCA procedure in parallel with the development process. Use of LCA in this way often entails the assessment of lab and/or pilot-scale processes to generate environmental load data, which can then be used to optimise the developing process. This data may also be used to compare with existing industrial processes, to demonstrate or identify the environmental advantages of the “novel” process over the existing activities.

Within all LCA's, the clear stipulation of goal and scope is essential, however, for emerging LCAs several elements require particularly careful attention. Clarity on the intended use of the output and the anticipated target audience need especially careful definition to ensure that methodological choices are correctly made and results reported in a manner appropriate to the needs. As will be demonstrated within the case studies discussed here, the differentiation of purpose has significant ramifications for methodological choices which are exacerbated for early-stage LCA and information on whether the study is for “hot-spot” identification or comparison with existing processes, together with whether the results are purely for internal use or future external publication must be agreed by all stakeholders at the outset.

For an appropriate and detailed LCA in practical decision-making, a wealth of information is required, which might be hard to obtain within the early phase of process design. Whilst inventory data collection for existing processes may be arduous, the task is exacerbated for lab-scale processes, with issues such as the use of unfamiliar and/or novel materials, significant differences in laboratory methods and equipment compared with those on an industrial scale and processing issues that differ from those at a larger scale.

Wider topics that can be investigated within an “early-stage” LCA are the exploration of many alternative pathways for the future, with features including diversity in feedstocks, fuel composition, and by-products. Emerging technologies and novel products are often significantly different from the established materials or processes they aim to replace, with operational, in-use, and disposal data all likely to differ. LCAs at this stage therefore pose a multitude of challenges due to scale issues and technology uncertainties, which make choice of functionality for assessment problematic.

The purpose of this paper is to highlight the methodological issues and complexities concerning the integration of LCA for early research, spanning differing technological spheres, through the collation of experience from case studies in three completely different sectors: nanotechnology, lignocellulosic biofuel, and novel food processing. Whilst researching the environmental impacts within these different areas, the authors identified many commonalities in the challenges and issues encountered, some of which, whilst similar to those encountered in standard LCA's, became more prominent and critical due to the requirement for speed of assessment for “novel” technologies. Kunnari et al. (2009) note that “*simplification of LCA cannot be avoided in the development of new products*”, however, even when simplified, using LCA for assessment of emerging technologies brings in complexities that must be acknowledged and understood by all stakeholders to enable effective development decisions to be made. The main issues discussed in this paper are comparability, scaling, data, and uncertainties. Each of the emerging technologies discussed within this paper are within the laboratory stage, or very early stages of industrial pilot schemes, and therefore LCA at this stage is key in order to ensure reduced environmental impacts, whilst expedience in providing results that are as representative as possible is paramount to support the required pace of development.

## 2 Case studies

Each of the three case studies represent areas where there is increasing research interest and so offer good examples for the use of LCA at an early phase. Although diverse in nature, the experiences gained through using LCA to assess environmental impacts as part of the development process within each case study area illustrate that such issues are not technology dependant, but span different sectors and are common to early stage LCA studies. This supports commentary by Nielsen and Wenzel (2002), Kunnari et al. (2009), and Tufvesson et al. (2013) who reported similar challenges within their particular research areas. For each case study, an overview is presented to enable work to be put into context.

## 2.1 Nanotechnology

Nanotechnology (the synthesis and manipulation of objects at the nanoscale, <100 nm) is an emerging multidisciplinary field. The inventory of consumer goods incorporating nanomaterials has increased by 521 % since the start of measurement in March 2006 (Woodrow Wilson International Centre for Scholars 2011); industrial applications are also being rolled-out at a similar rate of progress. Nanomaterials are found in numerous every day products, such as sun cream, antibacterial coatings, dirt repellent, and anti-crease textiles, and are used in medical imaging techniques. Despite increased understanding of the science and engineering behind nanosynthesis and likely nano-applications, very few published studies investigate the life cycle implications of nanomaterials (Bauer et al. 2008; Buchgeister et al. 2008; Gavankar et al. 2012; Kim and Fthenakis 2012).

Carbon nanotubes are, arguably, the most established examples of engineered nanomaterials with one of the earliest reported synthesis routes (Iijima 1991) and a material with wide-ranging emerging and near-term projected applications. However, the production of carbon nanotubes has only recently moved from laboratory to industrial, pilot-scale levels, and the selection of the “finalised” industrial process design is still under development (Zhang et al. 2011). Upadhyayula et al. (2012) recently reviewed the progress made in understanding the life cycle impacts of carbon nanotubes, concluding only seven examples of LCA publications presently available, all of which relate to laboratory and small-scale synthesis of nanotubes. Similarly, a more recent literature search by the authors yielded in the region of 20 examples of a life cycle approach being applied to the assessment of nanomanufacturing, materials, technologies—other than carbon nanotubes (e.g., Lloyd and Lave 2003; Ju-Nam and Lead 2008; Kushnir and Sanden 2011). The lack of life cycle information on nanotechnology is a matter for concern when attempting to quantify the holistic environmental benefits these materials may, or may not, deliver (Bauer et al. 2008; Som and Berges 2010).

The impacts of nano-specific environmental effects are wanting from all published LCAs of nanomaterials. Despite scientific evidence purporting to potential, albeit largely unquantified, human health risks (Oberdoester 2010), and wider ecological impacts (Wiesner et al. 2006), exact understanding and accounting of cause–effect and transport mechanisms of nanomaterials are still under development (Rickerby and Morrison 2007; Peralta-Videa and Zhao 2011). The lack of impact assessment methodologies to account for any potential “nano-impacts” result in LCA studies only going so far as to measure the energy usage and bulk material and chemical consumption when assessing nanotechnology impacts (Bauer et al. 2008; Gavankar et al. 2012; Kim and Fthenakis 2012).

## 2.2 Lignocellulosic biofuel

The use of bioenergy is promoted within the EU and UK through, for example, the Renewable Energy Directive (EC 2009) and the RTFO (Department for Transport 2012). However, there has been much discussion surrounding the sustainability of bioenergy, especially focusing around the food versus fuel debate (Royal 2008). For this reason, second-generation biofuels such as lignocellulosic biofuel are considered to be more beneficial than fuels made from crops that can also be used for food. With the focus on the sustainability issues surrounding biofuel, an increasing amount of published material in the area of biofuel LCA can be found, as outlined within Bessou et al. (2011). Although LCA work (Kim and Dale 2006) has shown environmental benefits associated with lignocellulosic ethanol, most studies have focused on assessing the farming systems with a generic assumption of the ethanol conversion process; very few have addressed any specific environmental issues for the conversion process. This is due to process uncertainties and the non-availability of commercial plant (Spatari et al. 2010). Despite extensive research on lab and small scale within the scientific community, there is presently no large-scale commercial lignocelluloses-to-ethanol facility. Thus, technology uncertainty and potential commercial scale operation parameters also contribute to the gap (Spatari et al. 2010).

## 2.3 Novel foods and food processes

LCA is an established tool for the assessment of whole-life impacts of food products, and Andersson and Olssen (1999) and Roy et al. (2009) provide information on the multitude and variety of LCA studies performed in this sector. In recent years, however, its popularity has soared with the increased focus on greenhouse gas accounting over the entire supply chain fostered by such initiatives as the UK “Carbon Label” and Sweden's “Klimatmärkning”. Edwards-Jones et al. (2009) note that “*in the future consumer and legislative responses to carbon labels may favour goods with lower emissions*”; a statement which highlights the importance of using LCA techniques to optimise environmental performance of food production at the earliest possible stage of development.

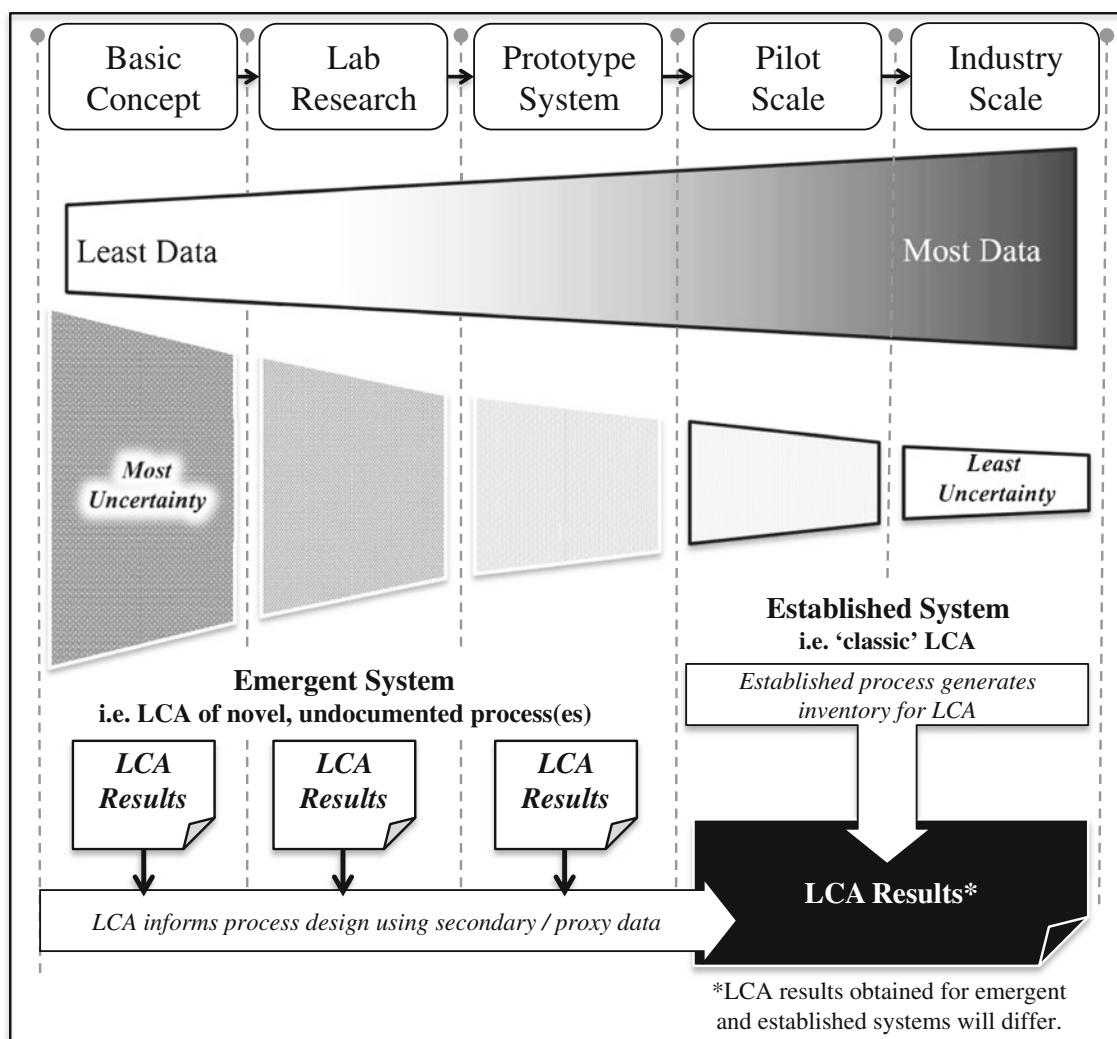
Despite the popularity of LCA within food manufacturing, and the obvious requirement for studies at the earliest possible developmental stage, there is very little published literature concerning LCA of “new processes” within food products or the challenges of performing LCA at this early stage. Pardo and Zufia (2012) reported on their study concerning LCA of food preservation technologies and Hospido et al. (2010) discuss some of the methodological issues associated with performing LCAs over novel food

products. The latter provides useful confirmation of some of the challenges identified with using LCA at this stage, with issues such as the inventory development stage, definition of functional unit, and the assumptions required to estimate future developments and uses all being highlighted. They propose a recommended approach within five identified areas, namely “type of LCA, functional unit, system boundaries, data gathering and scenario development” and advocate a check of its applicability to other industrial sectors.

### 3 LCA for early research

The majority of LCAs are traditionally performed at the pilot scale, where primary data can be readily acquired or industrial scale when the process is mature and thus generates necessary detailed inventory data. As indicated in Fig. 1, however, for LCAs on emerging technologies, there is no

“mature” plant available for data collection and a considerable amount of secondary and proxy data must be utilised. Whilst the requirement for and variability of this data may reduce as the development progresses, the future potential for development of such plant may in part be dependent on the verification of improved environmental credentials at the earliest stage. Such LCAs are typically commissioned to provide information for a variety of stakeholders including project researchers, developers, and decision makers, which may be internal project managers, external project financiers, or both. Practitioners of early stage LCAs must be sensitive to the increased levels of uncertainty that can be prevalent and ensure clarity on the intended and allowable use of results within the goal and scope. All information communicated must be commensurate with the needs of each stakeholder and the sensitivities or caveats of the study adequately explained to enable the recipients to appreciate the true nature of the results.



**Fig. 1** LCA at early research stage



### 3.1 Comparability

As previously highlighted, one of the objectives of performing LCA on emerging technologies can be to benchmark environmental performance against existing commercial products or processes. The problems of incomparable functional unit and system boundaries exist in all LCAs and are certainly not restricted to studies into novel processes; however, it is proposed that these problems are exacerbated when applying LCAs to early research and compounded by the required speed of assessment which is critical to enable development decisions to be taken in a timely fashion. Suh et al. (2004) confirms this, noting that choice of system boundary may have an influence on rankings in comparative studies, thus leading to incorrect conclusions and decisions about which products to promote. The function of the product may not be comprehensively defined, with systems prone to change when scaled up, processing stages may not be fully identified, co-product usage unclear, and end-of-life treatments unknown, all of which can result in the exclusion of processes and life cycle stages from the system boundary. Such actions can lead to inadequate interpretation of the results and incorrect decisions being taken.

Rapid advancement in nanomanufacturing practices, likened to that seen by the semiconductor industry (Klopper 2007), see advancements in tooling and production techniques resulting in process cycle times of 18 months (Krishnan et al. 2008). When practices, and therefore associated manufacturing data, are subject to changes within such short time periods the comparability of studies becomes much more difficult. The functional unit for many cradle-to-gate traditional bulk materials within nanotechnology is often based on the mass of a formed product. However, when dealing with nanomaterials, dominant functional changes can occur from subtle alterations in the surface area, structure, and purity of the product (Daniel and Astruc 2004). Thus, nanomaterials require a greater level of technical definition to be stated for the actual product formed and its applicability to specific applications (Wender and Seager 2011).

Functional equivalence is paramount, as stressed within Hospido et al. (2010), who suggest that for comparative studies only the part of the production chain that is affected by the change in production technique is included within the system boundary. This suggestion would be compatible with the observations of Kunnari et al. (2009); however, such simplification is not always possible if functional equivalence is to be achieved. “New” materials produced will not necessarily be direct replacements for their existing counterparts and as such will not be functionally equivalent as a stand-alone commodity. Their inclusion within an established process may often entail process or procedural changes within

the process or product system to be used and the functional unit chosen must be able to reflect and encompass this. For example during early stage LCA of oil body extraction from oilseeds, the “new” ingredient could not be compared with the ingredient it had replaced, since the “new” material possessed qualities and attributes that entailed the removal of several process steps and augmentation with others when incorporated into the production of an existing foodstuff. In this instance, the material needed to be compared as part of a food product system to ensure functional equivalence. Simplification of boundaries was not possible if functional equivalence was to be assured.

Similarly, the system boundaries of lignocellulosic biofuel can vary from study to study depending on the inclusion or exclusion of some processes. For the same supposed system boundary, e.g., well to gate, in terms of ethanol conversion process, the actual boundaries are not always clear, and in some studies the processes used have not been specified (Borrion et al. 2012). For example, among LCA studies published in this area, not all studies have taken account of chemicals, enzymes, nutrients, and the infrastructure such as equipment (MacLean and Spataro 2009). The decision to exclude certain elements of the process in the system boundary leads to problems, such as incomparability with similar studies and fossil reference systems. Functional equivalence may also be impossible to define when consumption patterns are altered by a new product, Bauer et al. (2008) suggest that in such cases the expected changes to the market and resultant effects on existing products need to be modelled. This links a more traditional attributional type LCA with a consequential LCA.

When applying LCA to early research, whilst speed of execution is important, information supplied to decision makers must contain clear statements and explanations of the complexities of the modelling undertaken. Clarity of purpose must be ensured within the goal and scope, with care taken to ensure that identical system boundaries are applied and functional equivalence is assured with any system used for comparison. Assumptions concerning future scenarios and technology development should be clearly labelled, functional units carefully selected, and, where appropriate, multiple functional units should be shown within studies to aid future comparisons. Whilst many of these aspects may not appear unique to early research LCAs, the way that the data may be used heightens their importance and makes clarity amongst all concerned essential.

### 3.2 Scaling issues

In order to conduct an LCA study, one must gather inventory data. For “standard” LCAs, this is typically industrial data

from established processes; however, this is clearly a problematic proposition for novel processes. Obviously, lab-scale processes do not entail the same level of complexity of equipment and commercial or industrial scale processes will almost certainly require additional processing elements such as material and heat transfer equipment (at the minimum) and entail the use of alternative processing equipment more suited to larger scale production. Conversely, at the lab-scale, processes may exhibit a far lower yield than would be possible in a commercial facility. For example, within a novel food processing project, the authors observed a lab-scale yield of approximately 10 % when producing a particular material; however, when this was transferred to pilot-scale for further testing, the larger-scale equipment was able to attain yields in the region of 80 %. Clearly, such a large discrepancy in the basic mass balance data would have an enormous impact on the overall results of an LCA and the assessment of viability of the process.

In the absence of peer-reviewed life cycle inventory datasets for nanomaterials, achieving confidence in the suitability of data collected from a particular laboratory scale synthesis route can be difficult. There are often a multitude of alternative reported synthesis routes for any given nanomaterial. In such cases, the LCA practitioner needs to establish, based on given technical, economical, or other related information, whether a particular nanomanufacturing process is likely to continue onto further stages of industrial development. In the case of carbon nanotubes (CNTs), many synthesis routes exist, each have merits and give rise to different structures and properties, but with only a few pilot schemes producing CNTs worldwide (Zhang et al. 2011), the process most likely to be adopted for widespread industrial growth of CNTs is a matter of considerable uncertainty. Failure to keep abreast of current material production methods could potentially result in, at best, wasted effort and, at worst, a misrepresentative and wholly inaccurate LCA; counterproductive in achieving the objectives of forecasting the impacts of emerging technologies.

Manufacturing at increasingly smaller scales is proving to be ever more energy intensive (Gutowski et al. 2010). Whilst efficiency gains are likely to be realised with larger-scale processes, the extraordinary energy intensity of nanoproducts, many orders of magnitude above existing traditional materials (Bauer et al. 2008; Kim and Fthenakis 2012), is likely to be a dominant area of the life cycle impacts. Subtle discrepancies in laboratory measurements could potentially lead to high orders of error when scaled up to larger production levels. As Khanna and Bakshi (2009) concludes, the projected LCA impacts may well be over-estimates when, in all likelihood, process yield and efficiency gains are realised at industrial levels (Khanna and Bakshi 2009). An area presently omitted

from many LCA studies is the specific impact attributable to the requirement of high precision instruments and bespoke infrastructure necessary in the formation of materials where precise control and monitoring is required to achieve the desired product. The omission of these elements hampers an accurate “full-scale” estimation of overall life cycle impacts.

The problem associated with scaling issues can be also observed from the variation of LCA results from lignocellulosic ethanol. As most research is still in the early stage of development and has not even reached the pilot-scale stage, process simulation is often used to generate data about the industrial-scale process. In such a way, lab-scale data and information from simulation can be used to assess the technology under development. The resulting assumption from process simulation, data generated, and predicted scales contribute to the uncertainties of LCA results. Additionally, lignocellulosic biofuel production is anticipated with cogeneration of by-products such as electricity and chemicals; the scale of biofuel production with the resulting scale of co-product will affect the choice of selected allocation methods. The results of LCA studies can be significantly influenced due to choices of different allocation method and these may well change as a result of the scale of the operation. For example, if the production of bioethanol from wheat straw is only done as a niche process then the allocation on a mass, energetic, or economic basis may be accepted, but if the production of bioethanol becomes the driver for the growth of a field of wheat, it may well be that economic allocation is more commonly chosen. Information regarding the sensitivities resulting from allocation must be reported and shared with all members of the development team to ensure that decisions concerning future direction of development are made appropriately.

Lack of published analysis concerning LCA of novel food processing makes determination of the impact of scaling issues difficult to quantify. Following the rationale proposed by Hospido et al. (2010), the boundary should be drawn such that the analysis concerns only that part of the production chain affected by the change in technique; however, in doing this, not only will small discrepancies take on a disproportionate importance but by neglecting certain elements of the process, full optimisation potential may be prevented due to certain environmentally critical aspects being overlooked. When comparisons are essentially of the changes within versions of the same novel process, e.g., if comparing the impacts of using different component solutions for soaking seeds within the same basic operation, the omission of data concerning equipment that would be required for a commercial facility may not be important, since that omission would be consistent across all comparisons. Difficulties arise, however, when comparisons are made against existing, established routes for producing the functionally equivalent foodstuff, for example where process

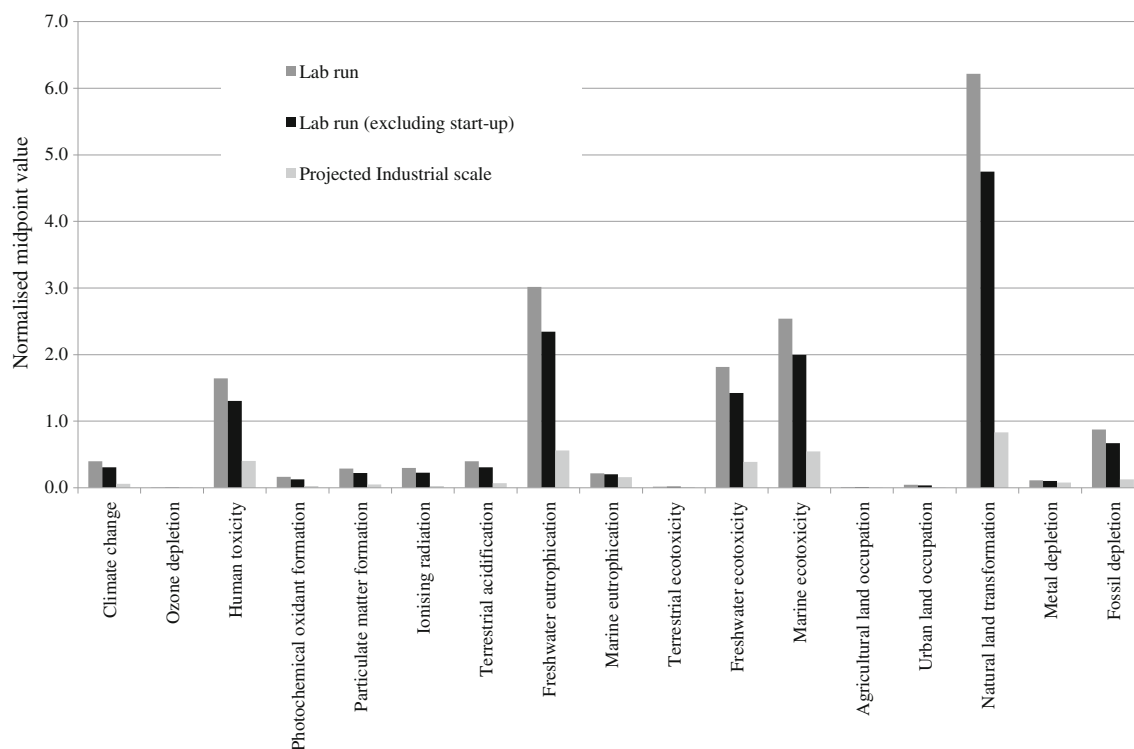
flows and life cycle inventories are developed based on an industrial scale processing facility with all the necessary ancillary equipment. Whilst an LCA can be developed using mass balance and collected energy usages from laboratory test runs, these will not be comparable with industrial scale processing.

Apart from the obvious difference in scale, laboratory production is often completed as a batch process with significant impacts on energy consumption for start-up and shut down, in addition to potential product wastage through clean-down of equipment. A comparative LCA was performed of the same process—production of food grade oil bodies using (1) laboratory measurements including energy for start-up; (2) laboratory measurements with start-up energy removed; and (3) laboratory mass balances projected as a continuous 50 t/day production unit, using manufacturers data for equipment energy consumption. Figure 2 shows the results generated in which it can be seen that even when removing the energy requirements for start-up of the batch production, there is a significant disparity between the projected industrial scale LCA and that generated using laboratory results alone. Even taking into account the additional energy requirements for material heating and transfer processes at the industrial scale, it is clear to see that basing an LCA on laboratory data alone would give rise to very different conclusions concerning the environmental credentials of the process and potentially lead to ill-informed decisions being made. This clearly links in

with the requirement to not only identify how the LCA results obtained will be used but also who will be viewing and using them, both at the time of presentation and in the future.

Other scale-up methods could potentially be used for LCA, for example, future scenarios of using new technologies can be estimated by using an economic input and output model to obtain national average data. Process simulation could provide material and energy flows at different scales for LCA and engineering design could supply infrastructure information, although the use of such design techniques may not always be successful due to lack of data and functionality within the simulation packages for modelling new processes and unusual or novel materials. It must also be noted that the use of these alternative methods for obtaining scale-up data could increase the uncertainty within the process to an even greater extent.

Throughout the three case studies outlined, the range of methods to overcome scaling issues is being investigated by the authors. With the issues outlined here, there could clearly be a case to say that the results from LCAs performed at this early development stage should never be published and that they should be consigned to internal use only. Certainly, the results from Fig. 2 would indicate that a study based purely on laboratory scale data should never be used to publish a comparative LCA against an existing commercial technology to an external audience. However, the authors would argue that publication of information concerning the impact



**Fig. 2** Comparison of oil body LCA using lab and projected industrial scale data: ReCiPe (2008) midpoint analysis

of scale-up within novel process LCA is important to be shared within the LCA community and that failure to do so would prevent progress in understanding the complexities and considerations presented by use of LCA at this early development stage. As such, dissemination of LCA results generated using the scaling techniques described here should be encouraged, providing such publications provide clear narrative on the complexities and sensitivities encountered, together with some estimation of uncertainty and adequate caveats on the use of the data. It is anticipated that future research in each case study will enable the publication of data concerning the uncertainties associated with scaling within LCA to help in the further quantification of this issue.

### 3.3 Data

For early-stage LCA work, speed of assessment is invariably an important factor for providing information at the stage in which changes to the process can most effectively be made and, as noted by Heinze et al. (1998), to minimise the time to production under patent protection. In this instance, use of secondary data is often the only practical solution since primary data would either not be available or take too long to gather. There is a wealth of publicly available inventory data for a wide variety of processes and substances. The European Commission Joint Research Council publishes a list of available databases, together with its own database of materials, the ELCD database (2012). However, novel processes can often involve the use of new materials or materials that are less prevalent as raw materials within existing processes, furthermore, as noted by Jimenez-Gonzalez et al. (2000), LCA databases represent just a part of the raw materials used in chemical and biochemical companies. The practitioner is thus faced with the dilemma of whether to invest time and resource in primary data collection or to attempt to utilise inventory data for a similar process as a proxy.

Missing datasets for nanomanufacturing processes is a large barrier in conducting valid LCAs. Nanomaterials can be broadly defined as taking particle, fibre, or plate forms; however, a diverse range of structures and sub-groups stem from these broad categories (ISO 27687 2008; Meyer et al. 2009). Nanomaterials with existing or high potential for future industrial applications are carbon based, composites, metals/alloys, biological, glasses, and ceramics (Bauer et al. 2008). Nanomanufacturing techniques are split: top down; broadly mass change processes and the formation of particles from larger parts, or bottom up; chemical synthesis utilising individual atoms or molecules as the material building blocks (Ju-Nam and Lead 2008). However, the number of different synthesis routes is continually growing and often unique to the specific nanomaterial formed (Luttge 2011). It follows, similarly to the assessment of chemicals, that a

generic LCA covering all nanomaterials cannot be produced (Klopper 2007); the requirement for bespoke nanomaterial datasets is thus required.

In response to missing nanomaterials data, inventory information for bulk material counterparts is often used in place of the actual nanomaterial. Modelling life cycle impacts using bulk materials alone omit downstream life cycle stages required in the production of nanomaterials, which among other factors, such as additional process complexities, have considerable additional energy demands (Bauer et al. 2008; Khanna and Bakshi 2009).

For LCA studies of the lignocellulosic ethanol conversion process, data such as material flow, energy flow, and infrastructure of industrial scale ethanol conversion plant are all needed. Whilst laboratory data could potentially be used to provide some of these, albeit with the issues as previously outlined in Section 3.2, studies taking into account the manufacturing processes often rely on simulations due to the lack of commercially available data. Together with functional unit and system boundaries, data inconsistencies contribute to the conflicting LCA results of lignocellulosic ethanol in the published literature (Borrión et al. 2012). As most research in the second-generation biofuel technology is at laboratory scale, with just a few pilot plant operations, detailed design data is not available in the literature (Searcy and Flynn 2008). Cherubini and Stromman (2011) also highlight the problem with data scarcity of advanced conversion technologies; the few studies that exist are mainly approximations based on mass or energy balances. Furthermore, there is a gap in LCA data for enzyme manufacture, which can vary in its energy input and emission outputs depending on both enzyme family and energy mix at the manufacturing location (Singh et al. 2010). Such data is not available in life cycle databases or published literature (Spatari et al. 2010).

As noted previously, there is a wealth of published literature concerning LCA studies on food ingredients and products, with approximately 40 such papers documented in the abstract and citation database SCOPUS, between 1999 and 2010 (Notarnicola et al. 2012). Despite this, the authors have found very little concerning LCAs for novel foodstuffs or processing, with Hospido et al. (2010) and Pardo and Zufia (2012) being two exceptions. Data gathering is one of the issues raised within Hospido et al. (2010) who recommend that specific data should be utilised for the foreground system, whilst average data—with a suitability check—be used for the background system. Within the novel food case covered here, there are several instances where data for previously undocumented materials is required, one of which is the treatment chemical to ensure microbial stability. Similar to the other two case studies, failure to access such data will necessitate the use of proxy materials to complete the LCA study based on the laboratory scale flow; however, if the process were to be commercialised, the activity that



requires the proxy data would almost certainly be replaced by a pasteurisation unit.

As shown in each of the case studies discussed here, increasing the coverage of databases and including emerging technologies such as enzymes and nanomaterials is essential for accurate use of LCA within the early stages of research. Where LCI data is not available, the usage and intended audience stipulated within the goal and scope will dictate whether time should be spent attempting to access data for such materials. Such efforts may not be beneficial or sensible where speed of assessment and reporting is required for internal decisions, particularly as the LCA can eventually be updated as more representative data becomes available (Kunnari et al. 2009) and such data may not be required for commercial scale LCA. However, where decisions are to be made based on LCA information generated using proxy materials, some form of sensitivity and uncertainty analysis must ideally be performed to retain the credibility of the model. This is absolutely paramount for communication of results to external parties. As with the previous three focus areas, ensuring that all parties concerned with the development process fully understand the complexities, assumptions, and limitations of any data used for the LCA conclusions presented is vital to ensure that decision making is performed appropriately.

### 3.4 Uncertainty

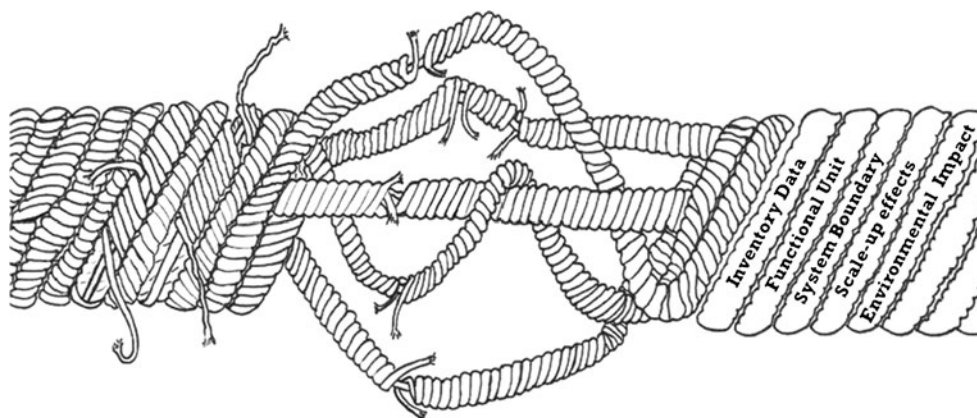
All LCA studies will have a certain degree of uncertainty and as noted by Heinzle et al. (1998) “*in the design process we can never be sure whether we know all important data and interactions*”. When conducting an LCA, it is important to understand how various processes and steps such as goal definition and scoping, inventory analysis, and impact assessment impact on the confidence in the results.

Clearly, the issues discussed so far within this paper all contribute towards uncertainty and the integrity of any LCA is dependent on restricting the degrees of uncertainty. Using

the analogy of a length of rope to represent a robust LCA study, each degree of uncertainty can be seen as a fray in one of the cords that form the rope. As depicted in Fig. 3, where the uncertainty is considerable, the fray becomes a break. When the number of frays is limited, the rope remains intact; however, when there are too many serious frays or break, the rope falls apart. Likewise, with an LCA if the level of uncertainty is too great, the integrity of the LCA is in such doubt that the study becomes at best meaningless and at worst dangerous, as a decision making tool. Given that LCAs on emerging technologies are most often generated to provide information upon which development decisions will be based, whether they be to modify a particular aspect of the process or whether to pursue the development at all, clarity concerning the sources and levels of uncertainty is paramount. The analyst must take absolute responsibility for ensuring that all decision makers are clear about the data provided to them.

Nanomaterials have only recently begun to be incorporated in mass consumer products and despite touted performance gains, the newness of nanoproducts result in little data in existence for in situ prolonged usage or disposal (Meyer et al. 2009). Nano-containing goods are subject to degradation with use, with primary effects on functional performance and the matter of released nanomaterials to the environment, the effects of which are of great uncertainty (Oberdörster et al. 2005; Som and Berges 2010).

Nano-specific end-of-life treatment is presenting challenges for existing waste and recycling practices and strategies (Breggin and Pendergrass 2007; Franco et al. 2007). Additional infrastructure and life cycle stages will foreseeably be required. Wastewater plants have been shown as ineffective in containing certain nanomaterials (Brar et al. 2010) and incineration proposed as a way of precious material retrieval and destruction of potentially harmful materials is facing problems such as the melting temperature of nanomaterials often being higher than bulk material counterparts (Olapiriyakul and Caudill 2009). Incineration can



**Fig. 3** Uncertainty for LCA at early stage

potentially release more thermally stable structures such as carbon nanotubes into the atmosphere (Franco et al. 2007). Recycling of nanomaterials is vital to close the loop and reduce the extraction from finite mineral and metal reserves, to justify the large investment in processing and energy inherent in nanomaterials, and will likely be a mandatory process in the future. However, the details are not formulated in any strategy; making the process of conducting LCAs on these emerging technologies all the more uncertain.

A typical LCA study of lignocellulosic biofuel consists of five main stages: biomass production, biomass transportation, biomass conversion to biofuel, biofuel transportation, and fuel use in the vehicle. Uncertainties can rise from any of these stages due to data quality, the assumptions made, regional practices, and so on. For example, within the biomass production stage, uncertainties can arise through the method for accounting and measuring indirect land use change, assumed irrigation practices and fertiliser usage. Within the biomass conversion process, enzyme production, co-generation of different by-products, and materials manufacturing can all contribute to a certain degree of uncertainty of an LCA result. In addition, future scenarios such as co-product generation and fuel supply can vary due to the market effect; this will lead to different allocation methods and different application of fuel end use contributing to the uncertainties of an LCA study.

With the creation of LCA studies for novel foodstuffs using alternative techniques, many levels of uncertainty have been encountered. Use of proxy data for seed pre-treatment chemicals, uncertain projections of yield for commercial scale variants of the lab process, and changing process requirements all compound the uncertainty that would normally be anticipated within an LCA.

Uncertainty in any LCA is important to quantify and report; however, the complexities and timescales involved with analysis of novel processes compound the issue such that the levels of uncertainty are greater and more invasive. Kunnari et al. (2009) note that conclusions should be formed (and hence decisions taken) only on the basis of clearly significant results. Assessment of significance can however be more problematic with the layers of modelling and uncertainty involved with emerging technology assessment and those responsible for delivering the results of such LCAs must ensure that the full details and implications are reported and fully understood by all concerned within the timescale required for decisions being taken.

#### 4 Implications

The growing trend in applying LCA for early-stage research can be observed from both outlines of current research

projects and within published literature, demonstrating increases in both analysts and audiences for such studies. Clarity of purpose must be paramount for LCAs on emerging technology, with the goal and scope clearly specifying how the results are to be used; whether they are intended to help inform decision makers of environmental “hot spots” and/or to compare the new process routes with current technology. The purpose of the study will affect methodological choices and requirements considerably and those involved with generating novel process LCAs need to ensure that all stakeholders are fully aware of the realities. Practitioners need to be particularly vigilant to the fact that the decision makers within the development cycle are most often not LCA experts and must therefore be fully apprised of the complexities, sensitivities, and uncertainties involved, which are far greater than for standard LCA. Whilst speed of analysis and reporting is of the essence, such vigilance in this area is vital to ensure decision making occurs appropriately.

In addition, as the use of LCA becomes more common and required within research, individuals that are not necessarily LCA experts may well take published material and use it for further study and comparison. Extraordinary care must therefore be taken to ensure that LCA for early research is not underestimated in terms of its complexity within the development cycle and is always performed by suitably qualified individuals.

Table 1 summarises the issues observed within the three case studies, with suggested actions to mitigate the challenges faced. In order to conduct an accurate and meaningful LCA at early research stage, issues such as system boundaries, functional unit, scaling issues, data, and uncertainties have to be acknowledged and addressed. Kunnari et al. (2009), advocated methodology adjustment to enable LCA to function as a tool for early assessment. From the examples provided here, it is apparent that many of the approaches suggested, e.g., scenario analysis, use of proxy data, documentation of uncertainties, can and must be adopted irrespective of the technology under investigation.

Furthermore, whilst LCAs based entirely on lab-scale data should be limited to internal decision making only, publication of data generated for early stage LCAs and findings from such studies that concern the four areas highlighted within this paper would be beneficial to the growing community of product and process developers and decision makers that wish to utilise LCA to its full effect within the development cycle.

#### 5 Conclusions

This paper highlights the research challenges and issues when applying LCA to early research as illustrated by case studies in three very different sectors, within which the four

**Table 1** Summary of main issues in using LCA for early research

| Main issues   | Challenges  | Suggested action for novel LCAs   |
|---------------|---|---|
| Comparability | New material not functionally equivalent to that which it replaces  | Expand system boundaries to establish functional equivalence wherever possible  |
|               | The function of the new technology not comprehensively defined  | Depict multiple functional units within studies where necessary, reporting all assumptions concerning future scenarios and technology development   |
|               | Consumption patterns (and thus market conditions) potentially affected by creation of new product                                       | Maximise clarity of purpose within goal and scope   |
|               |   | Report and fully explain all results and sensitivities to decision makers, ensuring full understanding  |
| Scale         | New technology will not entail the same level of complexity at the early stage of development as it will as an industrial scale process | Use process simulation and engineering design to generate data at different scales where applicable   |
|               | Lab-scale results suitable for hot-spot analysis but usage problematic as comparator for large scale                                    | Consider estimating future scenarios using economic input/output models to obtain national average data   |
|               | New processes may exhibit far lower yield at lab-scale than would be possible in commercial facility                                    | Wherever possible, results from iterative LCAs generated as new processes progress should be published, to build quantitative understanding on how scale-up affects results   |
| Data          | Lack of data for new materials  | Use representative proxy data where necessary to speed analysis, ensuring full details of uncertainties reported and explained to decision making team  |
|               | Primary data not available or would take too long to gather within development timescale  |   |
|               | Data quality reliant on the degree of technology development  | Provide references and details for data sources and calculation methods as part of novel LCA results  |
|               | Environmental impact assessment methodologies will lag behind the formation of new materials with potential impacts in the environment  | Provide detailed, characterised information regarding material(s) being investigated, to facilitate analysis of the environmental effects within future assessments   |
| Uncertainty   |   | Encourage publication of work wherever possible and use all data analysis to help in building databases for emerging technologies   |
|               | Unknown future applications   | Use estimates of use profile for the intended application, along with projected service life  |
|               | Unknown industrial scales   | Attempt to assess uncertainty wherever possible   |
|               | Data gaps   |   |
|               | The degree of technology development  | Provide transparent information regarding the source of uncertainty, uncertainty level, and sensitivities within the novel LCA report and ensure the importance and implications of these are fully understood by all, prior to decisions being taken |
|               | Unavailable in-use performance information  |   |

main areas discussed were comparability, scaling, data accessibility, and uncertainty.

Analysis of emerging products and processes intensifies the issues of comparability experienced with LCAs of established systems. Establishing a suitable functional unit and ensuring functional equivalence with current technologies can be more problematic than with standard LCAs, since future applications are not always clear and can be subject to change with the development of new technology. Scalability is one of the most significant problems when conducting an LCA for early stage. New technology under investigation at the basic concept or lab stage does not entail the same level of complexity as an equivalent industrial scale process and the new processes may exhibit far lower yield than would be possible in a commercial facility. In addition, different processing stages or materials may be required to overcome issues at lab scale that would not be evident in a commercial

facility where they would be redundant or replaced by more “efficient” alternatives. The resultant early stage LCA may have significantly more variables, complexities and scenarios than a “traditional” LCA, all of which may have a significant influence on the results generated and the ensuing assessment of process viability. Those responsible for generating such LCAs must ensure that all parties within the process/product development team are clear on the complexities and sensitivities involved, to ensure decisions are taken appropriately

The reliability of an LCA study at early stage is strongly dependent on the data used. Development of emerging technologies can often use materials that are either novel themselves or infrequently used within industry, with accessibility of inventory data an issue in both cases. Whilst primary data collection may be possible, the time taken for such an exercise is counterproductive to the required expedience for early

stage development. Use of proxy data will therefore be more prevalent in such early stage LCA studies, together with the use of data whose quality may not meet the desired level. The authors believe that whilst transparency of data is always important for LCAs, special emphasis should be placed on the reporting, explanation, and justification of data within early stage LCA reports such that data can be more easily adapted and augmented as updated information becomes available. In addition, where inventory data is generated pertaining to a material for inclusion within the LCA, that information should be placed in the public domain wherever possible to aid with the development of databases for future use. Published LCA studies reporting detailed inventories and characterised nature of materials are beginning to appear; examples include Griffiths et al. (2013a, b).

All LCAs have certain degree of uncertainty, and early-stage LCA is not unique in that. However, the source and magnitude of uncertainty increases with such LCA studies due to combined effects described. Failure to acknowledge the uncertainty and fully explore the caveats can result in inefficient use of the information gathered and inappropriate decision making at this key developmental stage. In recognising the difference and uncertainties of LCA within early-stage research, development of specific guidance for inclusions within the goal and scope for novel process LCA could be beneficial. These should potentially include the requirement for conclusions to be made only when clearly significant results are indicated, as suggested by Kunnari (2009), together with more expansive reporting guidelines to ensure all simplifications, projections, sensitivities, and uncertainties are not only documented, but adequately conveyed and explained to members of the development team to ensure their full understanding of the issues behind the results presented, before decisions are taken.

Finally, where results are generated from the step-wise improvement in quality of information that inevitably occurs as the technology development progresses, these should wherever possible be compared against initial results and reported within the public domain. This would enable development of a quantified understanding of the order of magnitude difference between early-stage results and those generated further down the development cycle.

## 6 Suggestions for the future

For increased understanding of both the issues concerning the process and the results of LCAs involving emerging technologies, it is important that information regarding their execution is published in the public domain. Clearly, there may sometimes be issues regarding the reporting of specifics for these projects since by their very nature they may contain

sensitive or confidential information; however, any information that can assist with the creation and understanding of methodologies for “novel” LCA studies, even if generalised to protect intellectual property, can only be beneficial. To that end, the authors intend to follow up this article in due course with an update of type and success of strategies used to overcome the challenges discussed here within their practical application. They would also encourage all fellow researchers involved with LCA work on novel processes to publish information beneficial to the development of this area.

**Acknowledgments** The authors would like to thank the funders of their individual research. This includes: EPSRC EP/H046305/1 Nano-Integration of Metal-Organic Frameworks and Catalysis for the Uptake and Utilisation of CO<sub>2</sub> (Griffiths and McManus), BB/G01616X/1, BBSRC Centre For Sustainable Bioenergy (BSBEC): Programme 4: Lignocellulosic Conversion To Bioethanol (LACE) (Li and McManus), the DEFRA Link Food Quality and Innovation Programme on the Sustainable Emulsion Ingredients through Bio-Innovation (SEIBI), and the University of Bath, UK (Hetherington and McManus). Many thanks are also given to the reviewers for their input and constructive feedback in the synthesis and improvement of this article.

## References

- Andersson K, Olssen T (1999) Including environmental aspects in production development: a case study of tomato ketchup. *Food Sci Technol* 32(3):134–141
- Bauer C, Buchgeister J, Hirschier R, Poganietz WR, Schebek L, Warsen J (2008) Towards a framework for life cycle thinking in the assessment of nanotechnology. *J Clean Prod* 16(8–9):910–926
- Bessou C, Ferchaud F, Benoît G, Bruno M (2011) Biofuels, greenhouse gases and climate change. A review. *Agron Sustain Dev* 31:1–79
- Borrión AL, McManus MC, Hammond GP (2012) Environmental life cycle assessment of lignocellulosic conversion to ethanol: a review. *Renew Sustain Energy Rev* 16(7):4638–4650
- Brar S, Verma M, Tyagi RD, Surampalli RY (2010) Engineered nanoparticles in wastewater and wastewater sludge—evidence and impacts. *Waste Manage* 30:504–520
- Breggin LK, Pendergrass J (2007) Where does the nano go? End-of-Life Regulation of Nanotechnologies. Washington
- Cherubini F, Stromman AH (2011) Life cycle assessment of bioenergy systems: state of the art and future challenges. *Bioresour Technol* 102:437–451
- Daniel MC, Astruc D (2004) Gold nanoparticles: assembly, supramolecular chemistry, quantum-size-related properties, and applications toward biology, catalysis, and nanotechnology. *Chem Rev* 104(1):293–330
- Del Borghi A, Binaghi L, Del Borghi M, Gallo M (2007) The application of the environmental product declaration to waste disposal in a sanitary landfill—four case studies. *Int J Life Cycle Assess* 12(1):40–49
- Department for Transport (2012) Revised RTFO guidance. <http://www.dft.gov.uk/publications/rtfo-guidance/>
- EC (2003) End of life vehicle regulations. <http://www.legislation.gov.uk/ukxi/2003/2635/contents/made>
- EC (2006) Waste Electronic and Electrical Equipment Regulations 2006. <http://www.legislation.gov.uk/ukxi/2006/3289/contents/made>



- EC (2009). Directive on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, Belgium: European Commission. <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:EN:PDF>
- Edwards-Jones G, Plassmann K, York EH, Hounsborne B, Jones DL, Mila i Canals L (2009) Vulnerability of exporting nations to the development of a carbon label in the United Kingdom. *Environ Sci Policy* 12:479–490
- Ekvall T, Weidema B (2004) System boundaries and input data in consequential life cycle inventory analysis. *Int J Life Cycle Assess* 9(3):161–171
- ELCD database (2012) <http://lca.jrc.ec.europa.eu/lcainfohub/datasetArea.vlm>. Accessed 15 May 2012.
- Finnveden G, Hauschild MZ, Ekvall T, Guinee J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S (2009) Recent developments in life cycle assessment. *J Environ Man* 91(1):1–21
- Franco A, Hansen SF, Olsen SI, Butti L (2007) Limits and prospects of the "incremental approach" and the European legislation on the management of risks related to nanomaterials. *Regul Toxicol Pharm* 48(2):171–183
- Gavankar S, Suh S, Keller AF (2012) Life cycle assessment at nanoscale: review and recommendations. *Int J Life Cycle Assess* 17(3):295–303
- Griffiths OG, O'Byrne JP, Torrente-Murciano L, Jones MD, Mattia D, McManus MC (2013a) Identifying the largest environmental life cycle impacts during carbon nanotube synthesis via chemical vapour deposition. *J Cleaner Prod* 42:180–189
- Griffiths OG, Owen RE, O'Byrne JP, Mattia D, Jones M, McManus MC (2013b) Using life cycle assessment to measure the environmental performance of catalysts and directing research in the conversion of CO<sub>2</sub> into commodity chemicals: a look at the potential for fuels from "thin-air". *RSC Advances*. doi:10.1039/C3RA41900B
- Gutowski TG, Liow JYH, Sekulic DP (2010) Minimum exergy requirements for the manufacturing of carbon nanotubes. 2010 I.E. Int. Symposium on Sustainable Systems & Technology (ISSST)
- Heinzele E, Weirich D, Brogli F, Hoffmann VH, Koller G, Verduyn MA, Hungerbühler K (1998) Ecological and economic objective functions for screening in integrated development of fine chemical processes. 1. Flexible and expandable framework using indices. *Ind Eng Chem Res* 37:3395–3407
- Hospido A, Davis J, Berlin J, Sonesson U (2010) A review of methodological issues affecting LCA of novel food products. *Int J Life Cycle Assess* 15:44–52
- Iijima S (1991) Helical microtubules of graphitic carbon. *Nature* 354:56–58
- ISO 27687 (2008) Nanotechnologies—terminology and definitions for nano-objects—nanoparticle, nanofibre and nanoplate: 16
- Jimenez-Gonzalez C, Kim S, Overcash MR (2000) Methodology for developing gate-to-gate life cycle inventory information. *Int J Life Cycle Assess* 5(3):153–159
- Ju-Nam Y, Lead JR (2008) Manufactured nanoparticles: an overview of their chemistry, interactions and potential environmental implications. *Sci Total Environ* 400(1–3):396–414
- Khanna V, Bakshi BR (2009) Carbon nanofiber polymer composites: evaluation of life cycle energy use. *Environ Sci Technol* 43(6):2078–2084
- Kim S, Dale E (2006) Ethanol fuels: E10 or E85—life cycle perspectives. *Int J Life Cycle Assess* 11:117–121
- Kim HC, Fthenakis V (2012) Life cycle energy and climate change implications of nanotechnologies. *J Ind Ecol*. doi:10.1111/j.1530-9290.2012.00538.x
- Klopffer W (2007) Nanotechnology and life cycle assessment: synthesis of results obtained at a workshop, Washington DC, 2–3 October 2006
- Koller G, Fischer U, Hungerbühler K (2000) Assessing safety, health and environmental impact early during process development. *Ind Eng Chem Res* 39:960–972
- Krishnan N, Boyd S, Somani A, Raoux S, Clark D, Dornfeld D (2008) A hybrid life cycle inventory of nano-scale semiconductor manufacturing. *Environ Sci Technol* 42(8):3069–3075
- Kunnari E, Valkama J, Keskinen M, Mansikkamäki P (2009) Environmental evaluation of new technology: printed electronics case study. *J Cleaner Prod* 17(9):791–799
- Kushnir D, Sanden BA (2011) Multi-level energy analysis of emerging technologies: a case study in new materials for lithium ion batteries. *J Cleaner Prod* 19:1405–1416
- Lloyd S, Lave L (2003) Life cycle economic and environmental implications of using nanocomposites in automobiles. *Environ Sci Technol* 37(15):3458–3466
- Lutge R (2011) Microfabrication for industrial applications, 1st edn. William Andrew, Boston, pp 91–146
- MacLean HL, Spatari S (2009) The contribution of enzymes and process chemicals to the life cycle of ethanol. *Environ Res Lett* 4:014001
- Meyer DE, Curran MA, Gonzalez MA (2009) An examination of existing data for the industrial manufacture and use of nanocomponents and their role in the life cycle impact of nanoproducts. *Environ Sci Technol* 43(5):1256–1263
- Nielsen PH, Wenzel H (2002) Integration of environmental aspects in product development: a stepwise procedure based on quantitative life cycle assessment. *J Cleaner Prod* 10(3):247–257
- Notarnicola B, Hayashi K, Curran MA, Huisingsh D (2012) Progress in working towards a more sustainable agri-food industry. *J Cleaner Prod* 28:1–8
- Oberdoester G (2010) Nanotoxicology: an emerging discipline evolving from studies of ultrafine particles (vol 113, pg 823, 2005). *Environ Health Persp* 118(9):A380–A380
- Oberdörster G, Oberdörster E, Oberdörster J (2005) Nanotoxicology: an emerging discipline evolving from studies of ultrafine particles. *Environ Health Perspect* 113(7):823–839
- Oberdörster G, Stone V, Donaldson K (2007) Toxicology of nanoparticles: a historical perspective. *Nanotoxicology* 1(1):2–25
- Olapiriyakul S, Caudill RJ (2009) Thermodynamic analysis to assess the environmental impact of end-of-life recovery processing for nanotechnology products. *Environ Sci Technol* 43(21):8140–8146
- Pardo G, Zufia J (2012) Life cycle assessment of food-preservation technologies. *J Cleaner Prod* 28:198–207
- Peralta-Videa JR, Zhao L (2011) Nanomaterials and the environment: a review for the biennium 2008–2010. *J Hazard Mater* 186(1):1–15
- Rickerby DG, Morrison M (2007) "Nanotechnology and the environment: a European perspective. *Sci Technol Adv Mat* 8(1–2):19–24
- Royal Society (2008) Sustainable biofuels prospects and challenges. Policy Document 01/08. ISBN 978 0 85403 662 2 [http://royalsociety.org/uploadedFiles/Royal\\_Society\\_Content/policy/publications/2008/7980.pdf](http://royalsociety.org/uploadedFiles/Royal_Society_Content/policy/publications/2008/7980.pdf)
- Roy P, Nei D, Orikasa T, Xu Q, Okadome H, Nakamura N, Shiina T (2009) A review of life cycle assessment (LCA) on some food products. *J Food Eng* 90:1–10
- Searcy E, Flynn PC (2008) Processing of straw/corn stover: comparison of life cycle emissions. *Int J Green Energy* 5:423–437
- Singh A, Pant D, Korres NE, Nizami A, Prasad S, Murphy JD (2010) Key issues in life cycle assessment of ethanol production from lignocellulosic biomass: challenges and perspectives. *Bioresour Technol* 101:5003–5012
- Som C, Berges M (2010) The importance of life cycle concepts for the development of safe nanoproducts. *Toxicology* 269(2–3):160–169
- Spatari S, Bagley DM, MacLean HL (2010) Life cycle evaluation of emerging lignocellulosic ethanol conversion technologies. *Bioresour Technol* 101:654–667
- Suh S, Lenzen M, Treloar GJ, Hondo H, Horvath A, Huppes G, Joliet O, Klann U, Krewitt W, Moriguchi Y, Munksgaard J, Norris G (2004) System boundary selection in life-cycle inventories using hybrid approaches. *Environ Sci Technol* 38(3):657–664

- Tischner U, Masselter S, Hirschl B, German Umweltbundesamt (2000) How to do EcoDesign?: a guide for environmentally and economically sound design. Verlag form: Frankfurt am Main
- Tufvesson LM, Tufvesson P, Woodley JM, Börjesson P (2013) Life cycle assessment in green chemistry: overview of key parameters and methodological concerns. *Int J Life Cycle Assess* 18:431–444
- Upadhyayula VKK, Meyer DE, Curran MA, Gonzalez MA (2012) Life cycle assessment as a tool to enhance the environmental performance of carbon nanotube products: a review. *J Cleaner Prod* 26:37–47
- Wender B, Seager T (2011) Towards prospective life cycle assessment: single wall carbon nanotubes for lithium-ion batteries. 2011 I.E. Int. Symposium on Sustainable Systems & Technol. (ISSST)
- Wiesner MR, Lowry GV, Alvarez P, Dionysiou D, Biswas P (2006) Assessing the risks of manufactured nanomaterials. *Environ Sci Technol* 40(14):4336–4345
- Woodrow Wilson International Centre for Scholars (2011) Project on Emerging Nanotechnologies: a nanotechnology consumer products inventory. <http://www.nanotechproject.org/inventories/consumer>. 4 March 2011
- Zhang Q, Huang JQ, Zhao MQ, Qian WZ, Wei F (2011) Carbon nanotube mass production: principles and processes. *Chemsuschem* 4(7):864–889